

Tools for Analyzing and Describing the Impact of Superstructure Blockage on Availability in Shipboard and Submarine Satellite Communications Systems

Roy A. Axford, Jr.
SSC San Diego

Gerald B. Fitzgerald
The MITRE Corporation

INTRODUCTION

On most of today's warships, it is impossible to find a single location for a satellite communications (SATCOM) antenna that provides an unobstructed view of the entire sky. If there is sufficient available topside space, two antennas are usually installed to support a mission-critical system (e.g., protected extremely high frequency [EHF] SATCOM). Lower priority systems are often forced to use a single antenna.

No matter how many antennas are used, it is critical to quantify the impact of topside blockage on the availability of a shipboard SATCOM system. Knowledge of this impact is needed in antenna location selection to ensure that the highest priority systems have the best views of the sky. Presenting this knowledge in an easily understood manner can make the topside design process more successful. Furthermore, once a shipboard antenna system is installed, the ship's company must have a clear understanding of the impact of unavoidable blockage on communications availability.

Many ship captains say that there are times when their choice of heading is dictated by whether or not a particular antenna system can "see" a desired satellite. It also appears that the determination of unblocked headings is often made by trial and error at sea, without benefit of *a priori* knowledge of the blockage situation of the SATCOM terminal in question. Topside blockage is so frequently discussed in the Fleet that there is widespread need for a software tool that can present this knowledge clearly.

This paper describes a set of tools for the analysis and display of the impact of superstructure blockage on shipboard SATCOM availability. These tools can give a ship's crew real-time indications of the blockage situation for an antenna system of interest with any desired geostationary satellite, based on the ship's present position, heading, and the Sea State. (Geosynchronous satellites in inclined orbits are discussed later in the Spatial Model section.) For route planning, there is also a display that shows the blockage situation along an entire Great Circle path as a function of Sea State (for the Great Circle headings). For more general planning and analysis, there is a display that shows the percentage of blockage-free headings (as a function of position and Sea State) as a colored cell on a global map. Along with their value to the operational community, these tools help topside designers compare the relative merits of candidate antenna installation locations.

ABSTRACT

The blockage analysis tools in the satellite communications (SATCOM) Availability Analyst (SA2) software package combine topside blockage data, communications satellite constellation positions, and ship-motion models to calculate the impact of superstructure blockage on availability as a function of antenna installation locations, ship's geographic position, and sea state. This impact can be evaluated for a specific position, along a ship's planned route, or averaged across the entire field of regard of the SATCOM constellation(s) of interest. This paper details the capabilities of the blockage analysis tools in SA2. The tools are applied to the analyses of topics of current interest including International Maritime Satellite (INMARSAT) on the CG 47 class, Global Broadcast Service (GBS) aboard the flagship USS Coronado (AGF 11), and submarine High Data Rate (SubHDR) on the SSN 688 class.

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The blockage analysis and display tools described here are components of a larger program called SATCOM Availability Analyst (SA2). The next section, Component Models, describes the lower-level components used to model the effects of blockage in SA2 (i.e., inputs). The Displays and Metrics section presents SA2's blockage analysis products (i.e., outputs). The Applications section gives some illustrative examples of SA2's recent application to the analysis of blockage for emerging SATCOM terminals to be installed on Aegis cruisers and *Los Angeles* class submarines.

COMPONENT MODELS

SA2 was developed as an extension of the Global Broadcast Service (GBS) Data Mapper (GDM) [1, 2]. GDM combined a simple Java-based Geographic Information System (GIS) with encodings of relevant International Telecommunications Union Radiocommunications (ITU-R) Recommendations and GBS link budget parameters to develop global maps of GBS link margin and availability.

Spatial Model

The core of SA2 is this same GIS, built upon a simple raster model of the earth's surface, which is represented as an array of $2.5^\circ \times 2.5^\circ$ *model cells* (between latitudes 70S and 70N). The model-cell center points are stored as 3-space (x, y, z) vectors. The model-cell size can be varied, but 2.5° represents a good trade-off between precision and run time for most applications.

SATCOM constellations in SA2 are also represented as sets of 3-space vectors—each vector giving the Clarke Belt position (CBP) of one geosynchronous satellite. SA2 computes the elevation and azimuth angles from the center point of any model cell to a satellite's CBP by using simple vector arithmetic. These angles may then be combined with a ship's heading (entered by the SA2 user), and used as indices into a blockage matrix. As described in the following section, this matrix is an image of the superstructure blockage as seen from each antenna assigned to the satellite of interest. Thus, SA2 computes whether or not a ship in a given model cell and on a particular heading has an unblocked line of sight (LOS) to the satellite of interest. In addition, the SA2 user may enter a Sea State. SA2 then uses ship-class-dependent motion models (described later in the section on Ship Motion Models) to expand the LOS from the antenna into an appropriately distorted cone, thus accounting for the impact on satellite visibility. Increased ship motion in higher Sea States reduces availability by causing the superstructure to move in and out of an antenna's LOS to the satellite of interest. As shown in examples below, some antenna locations suffer more from this effect than others.

Many geosynchronous communications satellites of interest are in inclined orbits (e.g., the Ultra-High-Frequency [UHF] Follow-On [UFO]/Global Broadcast Service satellites: UFOs 8, 9, and 10). The pointing angles to such satellites from a geographic position vary over the diurnal cycle. SA2 does not model this motion, but it is able to read satellite track files in the form of pairs of azimuth and elevation pointing angles versus time for the position and satellite of interest. Such track files are readily available from applications such as Satellite Tool Kit (STK) and Satellite Orbit Analysis Program (SOAP). SA2 can use these pointing angles similarly to those for geostationary satellites (i.e., a geosynchronous

satellite in an orbit with 0° of inclination with respect to the equatorial plane) to determine if the LOS is unblocked.

Blockage Models

Only the highest antenna on a ship can view the entire hemisphere of sky above it, and even then, only if the antenna is also the highest structure of any kind on the ship. Otherwise, additional antennas, masts, exhaust stacks, weapons, yardarms, or any other superstructure will mask out (i.e., block) some of the sky. The cluttered view of the sky from a shipboard SATCOM antenna's topside location is represented in SA2 as a two-dimensional, binary-valued matrix, with 360 columns covering azimuth angles in 1° increments, and 106 rows, covering elevation angles from -15° to the zenith (90°). (The zenith row is a degenerate case; all entries are identical.) Depression angles (elevation angles below 0°) must be included because as a ship rolls and pitches, the apparent elevation angle to a satellite near the horizon (relative to the ship's deck) may be negative.

Blockage matrices may be imported into SA2 by two methods. For installed terminals, the blockage information often already exists in a Blockage Adaptation Module (BAM) file generated from a digital image(s) of the view(s) from the antenna location(s). Alternatively, direct processing of such a digital image can create a blockage matrix for SA2. A suitable image could be acquired from the antenna's installation location with a fisheye-lens-equipped camera, but this method has not been used to obtain any of SA2's blockage data thus far. Almost all of the blockage data used in SA2 come from images generated by a three-dimensional computer-aided design (CAD) model of the ship's entire topside. Such topside models are often refined and/or updated by taking theodolite surveys of the ship's topside directly from the intended antenna installation location(s). (Reliance only on a ship's design drawings can lead to the omission of superstructure that was added after initial construction.) The image-processing software used is external to SA2.

The software can acquire and digitize images in either polar or rectangular projections, and the software is an extension of a MITRE-developed image processing and exploitation suite originally written for the National Imagery and Mapping Agency (NIMA). Figure 1 presents a CAD-model topside blockage image typical of those that have supplied most of the blockage matrices available within SA2.

Note that these matrices model boresight or optical blockage. SA2 does not consider the near-field patterns of shipboard antennas or effects such as knife-edge diffraction. (This approach is supported for frequencies above ~ 1 GHz by conclusions of a study [3] in which detailed tests and analyses were performed to determine the blockage effects of various topside structures on the performance of the AN/USC-38 EHF shipboard SATCOM terminal.) However, antenna beamwidth can be simulated within SA2 by a simple, run-time operation that pads each blocked area by a user-specified number of degrees. A similar procedure is often used in producing the BAM files of

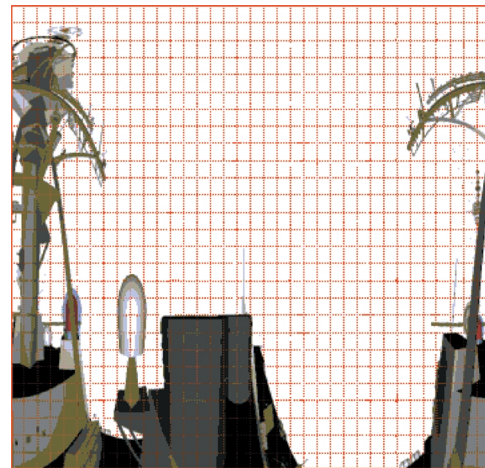


FIGURE 1. 3-D CAD topside model blockage image (rectangular projection) of the view from one of the INMARSAT antenna locations on the DDG 51 class.

dual-antenna systems to mark a "warning track" for the initiation of antenna handover procedures. Furthermore, BAM files often designate some of the smaller (say, less than 5 to 10 degrees in azimuth or elevation extent) unblocked areas as "blocked" to avoid "peep holes" that are lost due to ship's motion in moderate Sea States. This practice has also been adopted in producing the blockage matrices used SA2.

For dual-antenna systems, SA2 determines when an unblocked LOS to a desired satellite is available from *either* antenna or from *both* antennas. The "either antenna" mode analyzes systems that perform a hand-over from antenna "A" to antenna "B" as "A" moves into a "warning track." In these systems, either antenna can provide 100% of the communications services if it has an unblocked LOS to the satellite. The "both antennas" mode analyzes systems such as INMARSAT B High Speed Data (HSD) in which both antennas track the same satellite simultaneously to provide higher total throughput by using multiple transponder channels. In these systems, both antennas are required to provide 100% of the communications services.

Ship-Motion Models

As ships are accelerated by the wind and waves through which they travel, they experience Sea-State-dependent perturbations that are described by three rotational motions (pitch, yaw, and roll) and by three translational motions (surge, sway, and heave). These effects are detailed in [4]. Following McDonald's ranking of the magnitudes of these motions, SA2 confines itself to the impact of pitch and roll. Sea States high enough to make the other motions significant with respect to blockage are so severe that they surpass the operational specifications of Navy shipboard SATCOM antennas.

In [4], McDonald provides tables of length at the waterline, beam at the waterline, metacentric height and roll constants for various surface-ship classes. McDonald combines these constants with the ship-motion equations of DoD-STD-1399-301A [5] to provide ship-class-dependent pitch and roll extremes and periods as functions of Sea State. The resulting sinusoidal ship-motion equations are used to produce pitch and roll angles as functions of time for an animated display in SA2 in which the observer's frame of reference is the ship. These equations also allow the computation of temporal statistics (e.g., unblocked time/blocked time, durations of blocked times, etc.) that are of potential value in the evaluation of protocols for intermittent links.

Motion data are not as readily available for submarines. Since a helmsman actively controls the pitch of a submarine at periscope depth by using the stern planes, pitch is not a key factor in determining LOS availability at moderate Sea States. Roll is important, however. Submarine roll rates (even more than surface-ship roll rates), depend on the heading of the boat relative to the swell direction. For analyses of blockage aboard submarines, we have relied on interviews with former submariners to characterize the expected pitch-and-roll extremes and periods.

DISPLAYS AND METRICS

The data from the models described above are used in SA2 to provide blockage information for a ship's position along a route of travel or averaged over the entire field of regard of a satellite constellation of interest.

Ship's Position Blockage Information

SA2 provides an extremely useful display to assess the availability of a given SATCOM system from the ship's current position (or any position of interest) as determined by superstructure blockage and Sea State. Figure 2 provides three examples of SA2's SkyView display [6]. The currently selected blockage matrix (e.g., for a single antenna or for the composite blockage of two antennas) is always displayed in a polar orthographic projection. Ship's position may be typed in or entered by clicking on the desired spot on SA2's map display (see Figure 3). Ship's heading may also be typed in or adjusted with a slider. The satellites of the selected constellation (those above the horizon for the entered position) are then plotted as an overlay at the azimuth and elevation pointing angles computed for calm seas (i.e., for a level ship). Blocked satellites are shown in red, and visible ones are shown in green.

As noted above, the user can also examine the effects of Sea State with the SkyView display. Sliders allow the user to enter static pitch-and-roll angles based on, for example, the way the ship is behaving while underway (or to account for a list at the pier). The satellite's "dot" moves accordingly and turns red if it moves into a blocked region. Alternatively, using the pitch-and-roll magnitudes from [4], SA2 will plot the entire ship's motion envelope for a user-entered Sea State, resulting in green, red, or green and red "satellite smears" over the extent of pitch and roll. (Obviously, the user must correctly enter the ship's class for this approach to be useful.) The full equations of motion (according to the ship's class) may also provide an enlightening real-time animation of the apparent satellite positions. For example, see Figure 2 and imagine the satellite position moving according to the ship's equations of motion. (It is actually possible to get seasick while watching this display!) As the satellite moves, it turns red when blocked and green when unblocked. With all of these approaches, if any red appears, it indicates that the ship's motion might be causing intermittent outages for the SATCOM system in question. Thus, the SA2 SkyView display provides an aid for troubleshooting at sea.

Ship's Route Blockage Information

The SkyView display can help analyze SATCOM availability at a moderate number of positions, but availability along an entire ship's route is best viewed on SA2's TrackView display. With the aid of a text editor, the user enters pairs of end-points that are then connected by SA2 through use of a Great Circle route. The resulting tracks are color-coded along their extent according to the availability of the currently selected satellite or constellation of satellites.

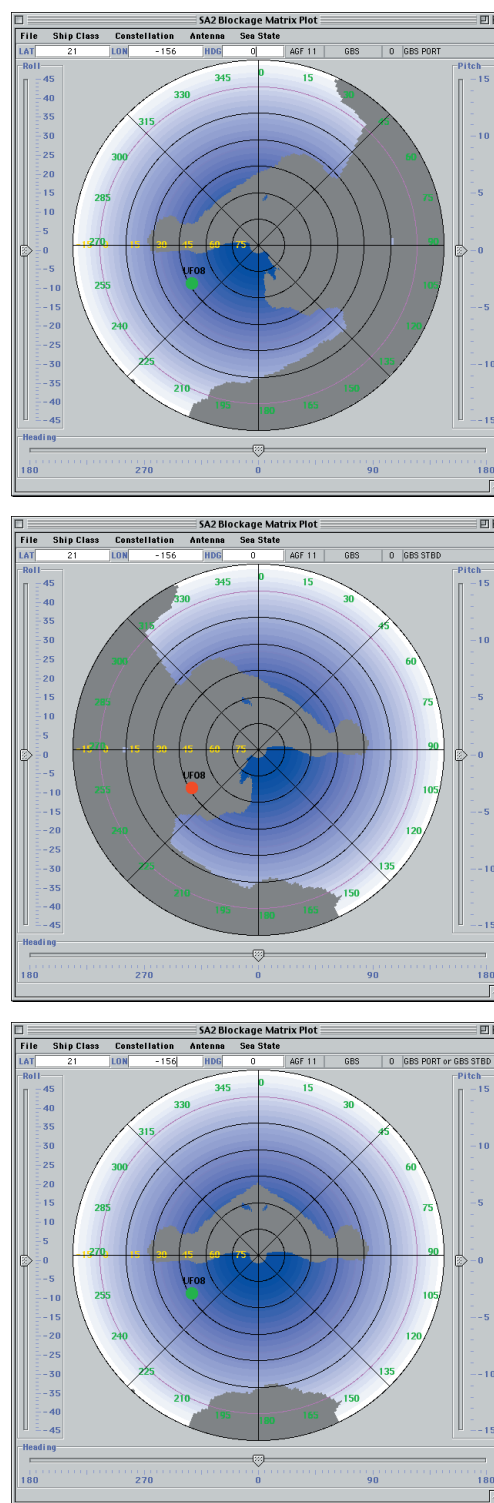


FIGURE 2. SA2 SkyView display for USS *Coronado*'s original GBS antenna installation locations. Top: port antenna. Middle: starboard antenna. Bottom: composite blockage for both antennas in "either antenna" mode.

The TrackView display can reflect different Sea States. It may also be animated at an accelerated speed of advance. In this animated mode, the SkyView display is slaved to the TrackView and updates as the track is traversed.

Figure 3 shows the TrackView display of the availability of the GBS due to blockage aboard USS *Coronado* (AGF 11) (corresponding to the blockage matrix in the bottom of Figure 2) in Sea State 4 along Great Circle routes between San Diego, CA, and Pearl Harbor, HI, and Yokosuka, Japan [6]. As with all SA2 TrackView displays, the blockage information plotted in Figure 3 assumes that the ship remains on Great Circle headings. With reference to the bottom of Figure 2, it is obvious that a significant number of *Coronado's* headings are blocked for GBS when the satellite in use appears above 30° elevation. This is most clearly seen using SA2's global blockage statistics and the Average Line-of-Sight Availability (ALA)View discussed in the next section.

Global Blockage Metrics

Normally, ships do not always maintain Great Circle headings while they are at sea. In general, a ship could be on any heading at a given moment depending on mission demands (e.g., flight quarters, zigzagging, etc.). Therefore, in considering the relative merits of alternative antenna installation locations, an important metric is *the percentage of headings that yield an unblocked LOS to the satellite of interest*. The following describes how SA2 calculates and displays this metric.

For any given Sea State, SA2 determines, for a combination of (1) satellite of interest, (2) ship antenna's location (or antennas' locations), and (3) ship's position and heading, whether the antenna(s) has (have) an unblocked LOS to the satellite of interest throughout the resulting ship-motion envelope. If, for a given position and heading, the satellite is visible throughout the entire ship-motion envelope, then that position is considered unblocked on that heading in the selected Sea State for the desired satellite. In performing this evaluation, by default, SA2 considers the heading blocked if the satellite is blocked at any point in the ship's motion envelope for the selected Sea State. This criterion is realistic for any bulk-encrypted link in which the encryption devices must "not miss a beat" to maintain synchronization. However, this criterion can be modified for alternative studies.

For each model cell, LOS availability is computed in the manner described in the preceding paragraph for all headings in 1° increments. The number of unblocked headings, divided by 360 and expressed as a percentage, is the ALA metric, a new figure-of-merit for analyzing blockage introduced in [6]. SA2 repeats this process for all spatial model cells. The resulting array of percentages is displayed as a color-coded map,

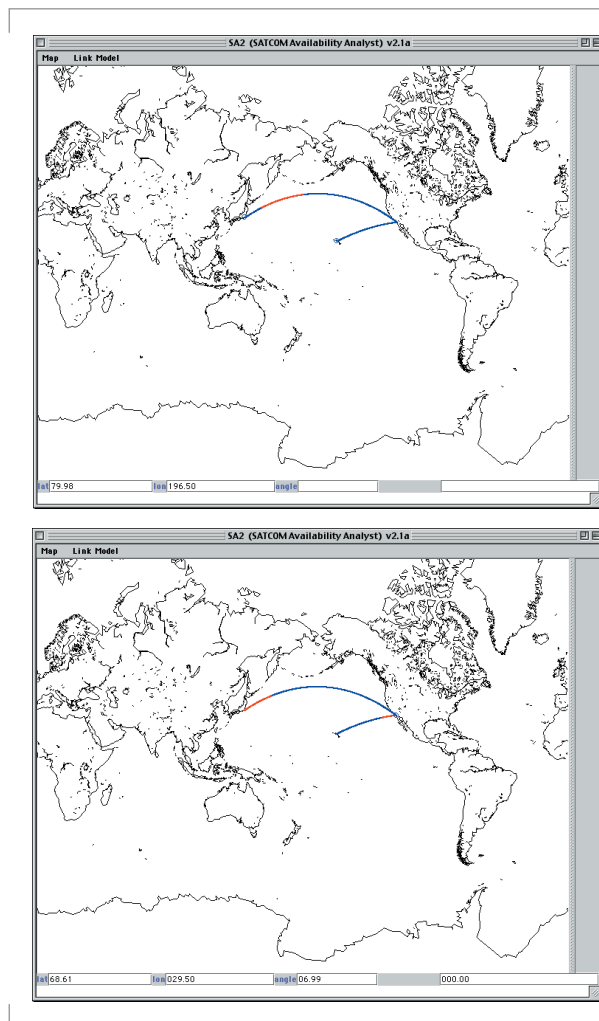


FIGURE 3. SA2 TrackView display for USS *Coronado's* original GBS antenna installation locations. Red: blocked; Blue: unblocked. Satellite in use: UFO 8. Sea State 4. Top: routes outbound from San Diego. Bottom: routes inbound to San Diego.

which is SA2's ALAView. These maps show, at a glance, where a particular shipboard SATCOM terminal is unblocked at all headings, at some headings, or at no headings. Figures 4A and 4B show ALAViews for the original GBS antenna installation locations aboard *Coronado*, in calm seas, and in Sea State 6, respectively, with the GBS transponders on Ultra-High-Frequency Follow-On (UFO) satellites 8, 9, and 10 [6].

The array of ALA figures spanning the satellite constellation's field-of-regard can also be averaged, yielding a *Global ALA* (GALA) metric. GALA can be calculated in two ways: (1) the average ALA over only ocean and littoral model cells within the field-of-regard or (2) the average ALA over all model cells within field-of-regard. SA2 uses the first definition by default.

APPLICATIONS

SA2 has been used recently to analyze INMARSAT B HSD availability aboard *Ticonderoga* class (CG 47) cruisers [7], submarine HDR (SubHDR-GBS and EHF) availability aboard *Los Angeles* class (SSN 688) submarines [8], and GBS availability aboard *Coronado* [6]. A detailed account of the *Coronado* work is reported in [6]. This section summarizes some of the conclusions of the CG 47 and SSN 688 analyses.

INMARSAT B HSD on the CG 47 Class

A commercial off-the-shelf (COTS) INMARSAT B HSD shipboard terminal has a single antenna and can support up to 64 kbps. To achieve 128 kbps throughput to the CG 47 and DDG 51 classes, it has been proposed to outfit each ship with two complete INMARSAT B HSD terminals. Additional INMARSAT space segment resources would be leased so that each ship would have access to an aggregate of 128 kbps by "summing" the 64 kbps channels from each terminal. Each COTS

INMARSAT B HSD terminal is an independent single-antenna system. There is no tracking hand-off from one terminal's antenna to the other. Therefore, to maintain a 128-kbps aggregate, each of the two antennas must be able to view the satellite continuously as the ship maneuvers. An analysis of the impact of blockage on the availabilities that this setup would achieve was accomplished using SA2's blockage tools in "both antennas" mode (see section on Blockage Models). For comparison, "either antenna" mode was also used.

Figure 5 shows ALAViews and GALA values for Sea States 0 and 6, in INMARSAT B HSD "both antennas" mode (128 kbps) and (a hypothetical) "either antenna" mode with handover (64 kbps) using the CG 47 class INMARSAT antenna installation locations. These results clearly show

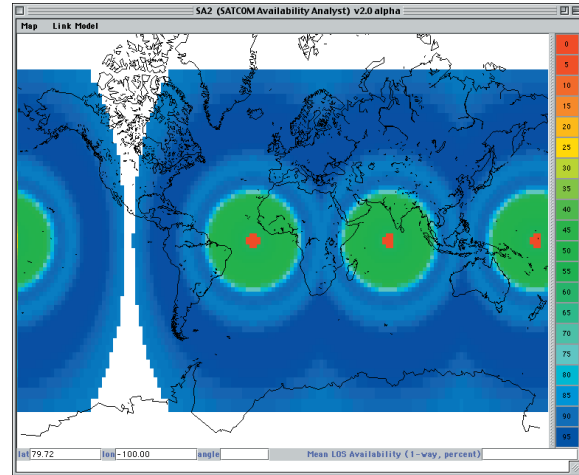


FIGURE 4A. ALAView for GBS aboard USS *Coronado*, original antenna installation locations, Sea State 0. GALA = 83.7%.

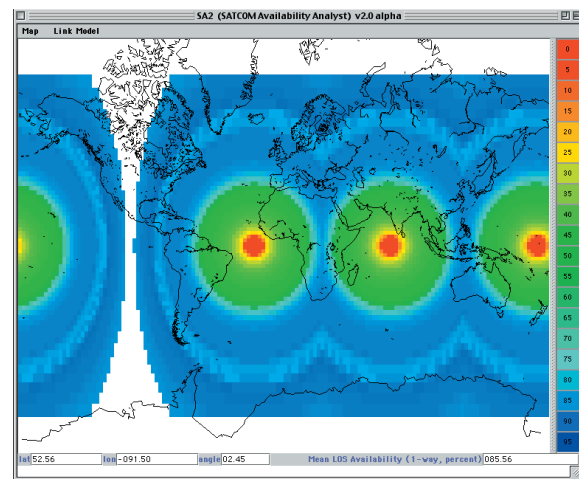


FIGURE 4B. ALAView for GBS aboard USS *Coronado*, original antenna installation locations, Sea State 6. GALA = 70.9%.

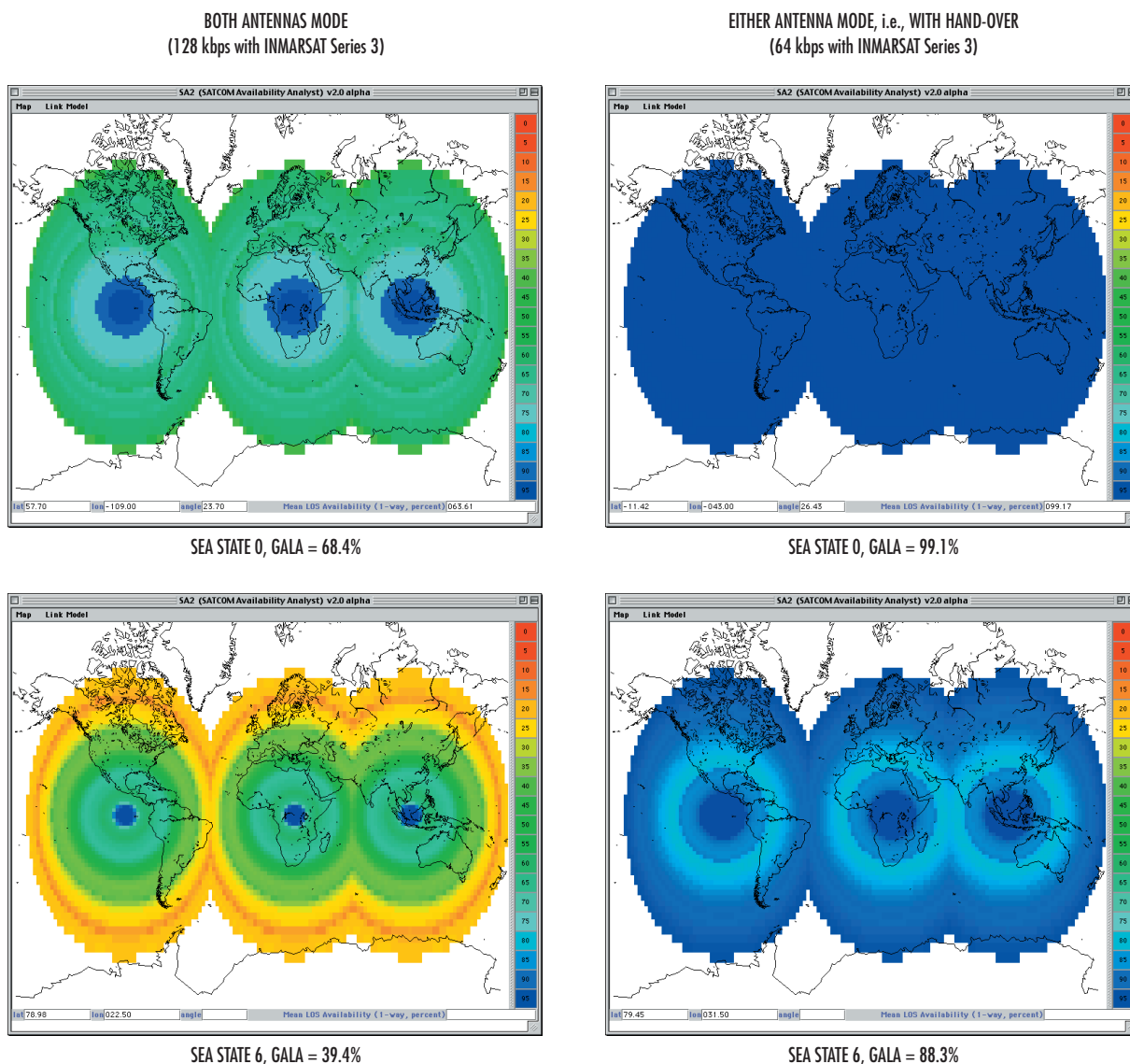


FIGURE 5. Dual-antenna INMARSAT availability on the CG 47 class analyzed with SA2's ALAView. Note: Only the three INMARSAT satellites on which leased services were offered at the time of the analysis are shown.

that a second, parallel INMARSAT B HSD terminal provides somewhat limited availability of a 128-kbps aggregate for the CG 47 class. However, the results also show that a dual-antenna INMARSAT terminal that would accomplish hand-overs between the two antennas provides an outstanding availability of 64 kbps, even in Sea State 6. After considering these results in July 2000, the Space and Naval Warfare Systems Command (SPAWAR) decided to investigate the development and acquisition of a handover-capable, dual-antenna INMARSAT B HSD terminal. Note that the next series of INMARSAT satellites, Series 4, will provide single-channel data rates up to 400 kbps, potentially making a handover-capable, dual-antenna INMARSAT terminal an even more valuable asset.

SubHDR on the SSN 688 Class

It is perhaps initially surprising that blockage is an issue for submarines, since the topside environment would appear to have no obstructions. In fact, Figure 6 shows there are several structures in close proximity to one another on the sail of the SSN 688 class. The short distances between them causes each to subtend a large solid angle as seen by the others. Furthermore, the masts and periscopes can be raised or lowered independently to variable heights.

The SubHDR system brings multiband SATCOM to submarines, including enhanced EHF capabilities and GBS. Early sea trials of the SubHDR mast and antenna system aboard USS *Providance* (SSN 719) revealed that from positions in the North Atlantic, the LOS to UFO 9 was sometimes blocked.

For analyses of SubHDR availability, SA2 represents the periscopes and other masts independently, each as seen from the point of view of the SubHDR antenna. Thus, the number of possible blockage matrices is large, but not all of them are tactically significant. For example, by doctrine, when a submarine is at periscope depth and any mast is raised above the waterline, a periscope must also be raised. Figures 7 and 8 present examples of SubHDR blockage matrices, which correspond to the first and sixth rows of Table 1. In all cases, the SubHDR mast is lowered 14 inches from its maximum possible height to avoid blocking the periscope. Table 1 shows GALA figures for six cases of equipment raised in addition to the SubHDR mast. In Sea State 3, the SubHDR GALA figure for the GBS payloads on UFOs 8, 9, and 10, or for the EHF LDR payloads on the same spacecraft, is, at best, 90% if the Type 8 Mod 3 periscope is used and 85.7% if the Type 18 is used. Figure 9 shows an ALAView for SubHDR, assuming that only the Type 18 periscope is raised.

Clearly, it is possible to analyze blockage for submarines with SA2 by using the same tools employed for surface ships. However, at sea, blockage is a somewhat different issue for submarines than for surface ships because submariners are generally more at liberty to select blockage-free headings after reaching periscope depth (PD). For example, submariners are never concerned about orientation with respect to wind direction in order to launch or recover aircraft. Furthermore, submariners often do not stay at PD

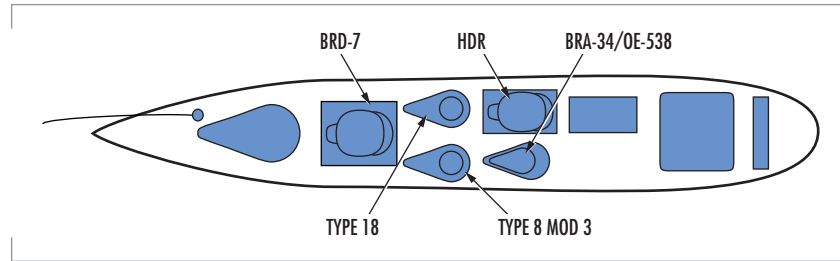


FIGURE 6. Sail configuration for USS *Providance* (adapted from [9]). The Types 8 Mod 3 and 18 are periscopes. The BRD-7 and BRA-34/OE-538 are multi-purpose masts.

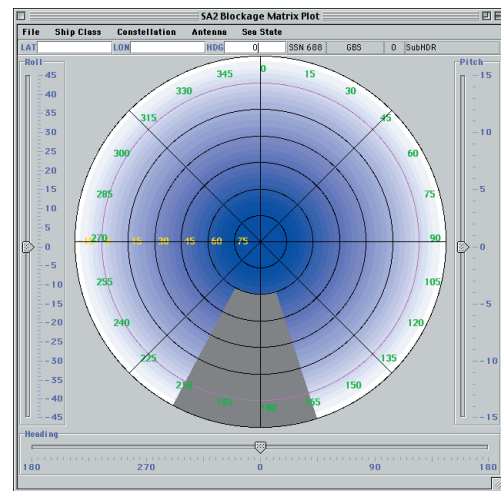


FIGURE 7. SubHDR blockage matrix when only the Type 18 periscope is raised.

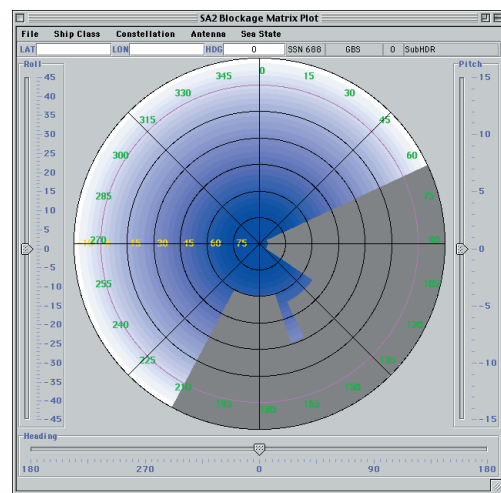


FIGURE 8. SubHDR blockage matrix when both periscopes are raised (Types 8 Mod 3 and 18) as well as both the BRA-34 and BRD-7.

any longer than is necessary to send and receive a few queues of communications traffic. On the other hand, in rough seas at periscope depth, submariners prefer to select headings more or less directly into the swells in order to minimize roll. In any event, SA2's SkyView display is useful to submariners for selecting blockage-free headings when using SubHDR.

SUMMARY

SA2 combines a set of simple mathematical models of the earth and of satellite constellations, coupled with similarly straightforward models of ship motion and of superstructure blockage to produce a powerful tool for assessing the impact of blockage on shipboard and submarine SATCOM availability. All of these components were previously available in various forms, but they had never before, to our knowledge, been combined in a single, simple-to-use package.

This paper has shown that various metrics are necessary to fully describe the impact of superstructure blockage on SATCOM availability over the full set of conditions in which ships and submarines serve. We also believe that this paper and our experiences using SA2 to interact with personnel from the operational, acquisition, and RDT&E communities have demonstrated that colored graphical displays are not just desirable, but are necessary to fully convey the impact of blockage on SATCOM availability.

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*now SSC San Diego

TABLE 1. GALA figures for GBS via SubHDR aboard the SSN 688 class for various combinations of equipment raised. The combinations represented by italicized rows, while technically possible, are not allowed by submarine doctrine.

Equipment(s) Raised (in addition to SubHDR)	GALA (%)	
	Sea State 0	Sea State 3
Type 18 Periscope	89.4	85.7
<i>BRA-34 Mast</i>	<i>83.7</i>	<i>79.5</i>
Type 8 Mod 3 Periscope	93.2	90.0
<i>BRD-7 Mast</i>	<i>96.4</i>	<i>94.9</i>
Type 18 and BRA-34	73.1	65.2
Types 8 Mod 3 and 18 plus BRA-34 and BRD-7	66.0	59.1

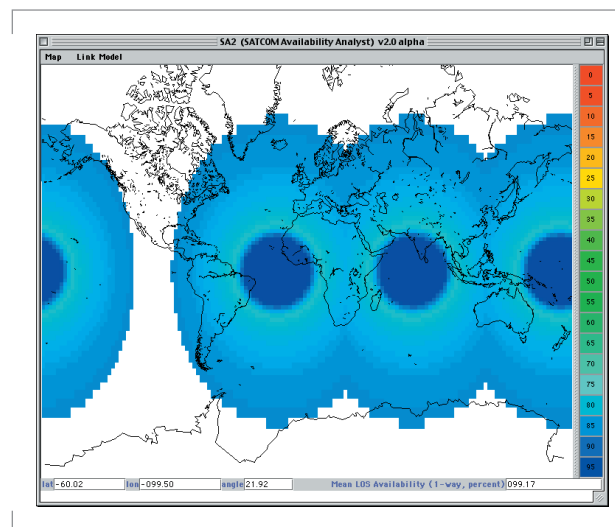


FIGURE 9. ALAView for GBS via SubHDR aboard the SSN 688 class. Type 18 periscope is raised; SubHDR mast is lowered 14 inches from its maximum possible height. Sea State 3. GALA = 85.7%.

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Roy A. Axford, Jr.

Ph.D. in Electrical Engineering,
Communications Theory, and
Systems, University of
California at San Diego, 1995
Current Research: Technologies
for wideband mobile satellite
communications.

Gerald B. Fitzgerald

BA in Linguistics and Computer
Science, Yale, 1977
Current Research: RF propaga-
tion modeling; imagery and
SIGINT fusion; network
intrusion detection.

*For further information, contact author.